

# SCENARIOS OF GRAVITINO DARK MATTER AND THEIR COSMOLOGICAL AND PARTICLE PHYSICS IMPLICATIONS

G. MOULTAKA\*

*Laboratoire de Physique Théorique et Astroparticules  
UMR5207-CNRS, Université Montpellier II  
Place E. Bataillon, F-34095 Montpellier Cedex 5, France  
\* E-mail: Gilbert.Moultaka@lpta.univ-montp2.fr  
www.univ-montp2.fr*

I report on some scenarios where the gravitino is the dark matter and the supersymmetry breaking mediated by a gauge sector.

*Keywords:* Supersymmetry; Dark Matter; Gravitino; BBN.

## 1. Introduction

Providing a viable particle candidate for the non-baryonic dark matter (DM) in the Universe has become one of the main test requirements for model building beyond the standard model (SM) of particle physics. It is well-known (see for instance<sup>1</sup>) that an electrically neutral particle, weakly interacting with the primordial plasma and with a mass of order the electroweak scale ( $\lesssim \mathcal{O}(1 \text{ TeV})$ ) would have today a relic density  $\Omega \simeq 1$ , provided it is stable or sufficiently long-lived, thus putting  $\Omega h^2$  in the ballpark of the WMAP results.<sup>2</sup> It should then not come so much as a surprise that most scenarios beyond the SM can provide potential solutions to the dark matter mystery, even less take it as an indication for their particular physical relevance. Rather, one should keep in mind that *i*) the abovementioned estimate of  $\Omega$  assumes a simple thermal history of the early Universe *ii*) only a few classes of the proposed scenarios beyond the SM are theoretically framed in what was their motivation in the first place, i.e. solve the shortcomings of the standard model of particle physics.

We take hereafter point *ii*) as our guiding principle and address the question of dark matter from that point of view. We will then see that the assumption of point *i*) does not always apply in typical parameter space

regions of the scenarios under consideration.

## 2. Supersymmetric extensions

The supersymmetric (SUSY) extensions of the SM are among the most fashionable examples of *ii*), including (at least) the ingredients of the minimal supersymmetric standard model (MSSM). Yet not all of them provide a DM candidate in the configuration *i*). However, supersymmetry breaking being the trigger of the electroweak symmetry breaking, it is justified to study on the same footing the physical consequences of different SUSY breaking and mediation scenarios. For instance, in gravity mediated SUSY breaking scenarios,<sup>3,45</sup> it is natural to expect the gravitino mass  $m_{\tilde{G}}$  to be of order the electroweak scale, thus leaving room for a massive neutral weakly interacting particle such as a Neutralino to be the lightest SUSY particle. If stable, such a particle would perfectly fit point *i*) and provide a very good DM candidate. This tremendously studied scenario since the work of,<sup>6,7</sup> as natural as it may look, still relies on two crucial assumptions: the lightest susy particle (LSP) is not electrically charged (typically such as the tau slepton ( $\tilde{\tau}$ )) and there is a residual R-parity guaranteeing the stability (or at least a sufficiently long lifetime) of the lightest Neutralino. Theoretically, these two assumptions are not necessarily favored<sup>a</sup> since they can strongly depend on the actual dynamical mechanism underlying SUSY breaking, which is still poorly understood. An alternative option which has attracted much attention in recent years is to take the gravitino as the LSP, another logical possibility within the context of gravity mediated supersymmetry breaking, see for instance.<sup>8</sup>

In this presentation we put the focus on a different kind of scenarios where the SUSY breaking and its mediation to the supersymmetric standard model is realized through some gauge interactions,<sup>9-17,18-20</sup> The models originating from this class of gauge mediated susy breaking (GMSB) scenarios are phenomenologically as compelling as the gravity mediated ones, and have similar theoretical uncertainties. An important difference however is that here the gravitino is very light and *necessarily* the LSP, rather than this being a possibility among others. As usual, one can concoct exceptions. (See for instance<sup>21</sup> for a model where the gravitino is not the LSP, bringing the case back to the Neutralino DM configurations.) We stick however to the generic GMSB, assuming  $m_{\tilde{G}} \lesssim \mathcal{O}(1 \text{ GeV})$ ; in this case

<sup>a</sup>apart from the requirement itself of tailoring a DM candidate!

the DM issue is somewhat tricky, and in particular does not quite fit point i).

### 3. The phenomenological GMSB

We recall hereafter the main phenomenological ingredients of the gauge mediated susy breaking models based on the assumption that the leading contribution to the dynamical susy breaking is originating from some strongly coupled gauge sector (SBGS), screened (often dubbed 'hidden' or 'secluded') from the visible MSSM sector by some intermediate non-gauge interactions.<sup>18–20</sup> The various sectors are schematized as boxes in Fig. 1 and the interactions among them indicated by the arrows. The two messenger sectors are formed of matter chiral superfields  $\hat{\Phi}_M, \hat{\bar{\Phi}}_M$  and  $\hat{\phi}_m, \dots$ , having rather similar status; they have gauge interactions respectively with the visible MSSM sector and the hidden susy breaking sector, and non gauge interactions, through the superpotential, with an intermediate spurionic chiral superfield  $\hat{S}$ .  $\hat{\Phi}_M$  and  $\hat{\bar{\Phi}}_M$  have quark-like or lepton-like charges under  $SU(3)_c \times SU(2)_L \times U(1)_Y$ ,  $\Phi \sim (3, 1, -\frac{1}{3})$  or  $(1, 2, \frac{1}{2})$ ,  $\bar{\Phi}_M \sim (\bar{3}, 1, \frac{1}{3})$  or  $(1, 2, -\frac{1}{2})$ . To preserve gauge coupling unification these fields are usually put into larger gauge group multiplets, e.g.  $\mathbf{5} + \bar{\mathbf{5}}$  or  $\mathbf{10} + \bar{\mathbf{10}}$  of  $SU(5)_{\text{GUT}}$ , and  $\mathbf{16} + \bar{\mathbf{16}}$  of  $SO(10)_{\text{GUT}}$ . The other messengers  $\hat{\phi}_m$  are charged under some gauge group  $\mathcal{G}$  through which they feel the properties of the susy breaking (secluded) sector.<sup>b</sup> Furthermore, the messenger fields on both sides are assumed to interact only indirectly via  $\hat{S}$  through the superpotential  $W \supset W_S + \Delta W(\hat{S}, \hat{\phi}_i) + W_{\text{MSSM}}$  where,  $W_{\text{MSSM}}$  is the visible sector superpotential,  $W_S = \kappa \hat{S} \hat{\Phi}_M \hat{\bar{\Phi}}_M + \frac{\lambda}{3} \hat{S}^3$  and  $\hat{S}$  is neutral under all the gauge groups involved.

In the sequel we will be mainly interested in the three sectors on the right-hand side of Fig. 1. The conditions under which it is justified to ignore the effects of the two other sectors in the early Universe will be touched upon in Sec. 5. From the phenomenological point of view, all we need to assume here about these two sectors is that they cooperate to give non-zero vacuum expectation values (vev),  $\langle S \rangle$  and  $\langle F_S \rangle$ , respectively to the scalar and F-term components of  $\hat{S}$ . This gives a supersymmetric mass  $M_f = \kappa \langle S \rangle \equiv M_X$ , to the (Dirac) fermion component as well as SUSY breaking mass spectrum  $M_{s\pm} = M_X (1 \pm \frac{\kappa \langle F_S \rangle}{M_X^2})^{1/2}$  to the mass eigenstates of

<sup>b</sup>We do not enter here the fascinating question of susy breaking through non-perturbative gauge interaction phenomena supposed to occur in the latter sector, which were studied since the early eighties (see<sup>22,23</sup> for reviews) and rejuvenated recently.<sup>24</sup>

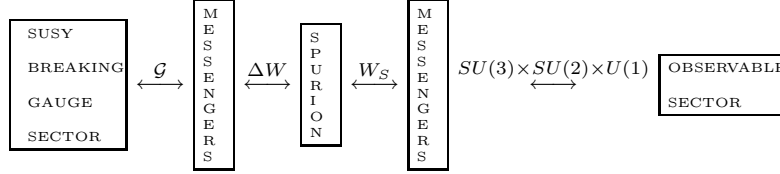


Fig. 1. generic structure of GMSB model sectors.

the scalar components of the  $\hat{\Phi}_M, \hat{\bar{\Phi}}_M$  fields. The amount of susy breaking transmitted to the messenger/MSSM sectors,  $\langle F_S \rangle$ , is in general only a fraction of the total amount of the SUSY breaking in the SBGS which we denote  $\langle F_{\text{TOT}} \rangle$ . The fermionic component  $\psi_S$  of  $\hat{S}$  will then carry a fraction of the goldstino in the form  $\psi_S = \frac{\langle F_S \rangle}{\langle F_{\text{TOT}} \rangle} \tilde{G} + \dots$ . It will thus contribute to the coupling of the massive gravitino to matter via its spin- $\frac{1}{2}$  component. Last but not least, the SUSY breaking is communicated to the visible sector through the gauge interactions of the messengers, leading to gaugino and scalar soft masses in the MSSM respectively at the 1- and 2-loop levels in the form  $M_i \sim \left(\frac{\alpha_i}{4\pi}\right) \frac{\langle F_S \rangle}{M_X}$  and  $\tilde{m}_a^2 \sim \left(\frac{\alpha_a}{4\pi}\right)^2 \left(\frac{\langle F_S \rangle}{M_X}\right)^2$  (where  $\alpha_{i,a}$  denote the SM gauge couplings or combinations thereof, and we have dropped for simplicity detailed flavor, messenger number and loop dependent coefficients). Assuming a typical grand unified group, the full MSSM and messenger spectrum and couplings depend uniquely on three continuous and one discrete parameters, namely  $M_X$ ,  $\frac{\langle F_S \rangle}{M_X} (\equiv \Lambda)$ ,  $\tan \beta$  (the ratio of the two higgs doublet vevs), and  $N_{\text{mess}}$  the number of quark-like/lepton-like messenger multiplets of some GUT group.<sup>c</sup>

Finally we note that the model defined so far possesses a discrete symmetry implying the conservation of the number of messengers in each physical process. An important consequence is that the lightest messenger particles (LMP) with mass  $M_{s-}$  will be stable due to such a symmetry. As we will see in Sec. 5 such stable particles can have a dramatic cosmological effect. Furthermore, depending on the GUT group multiplets they belong to, the mass degeneracy of these LMPs can be lifted by quantum corrections<sup>25,26</sup> leading to an LMP with very specific quantum numbers; e.g.  $\tilde{\nu}_L$ -like or  $\tilde{e}_L$ -like, if in a  $\mathbf{5} + \bar{\mathbf{5}}$  of  $SU(5)$ , an electrically charged  $SU(2)_L$  singlet, if in a  $\mathbf{10} + \bar{\mathbf{10}}$  of  $SU(5)$ , and an MSSM singlet, if in a  $\mathbf{16} + \bar{\mathbf{16}}$  of  $SO(10)$ .

<sup>c</sup>for simplicity we fix the couplings relevant to the interactions with the spurion as  $\kappa, \lambda \simeq 1$  in  $W_S$ , and choose the MSSM  $\mu$ -parameter to be positive; note also that the trilinear soft parameter  $A_0$  is vanishing to leading loop order.

#### 4. Coupling to Supergravity

The gravitino being the gauge field of local supersymmetry and the superpartner of the graviton, its proper inclusion in the model of the previous section necessitates the coupling of the latter to supergravity. The ensuing rich structure allows to determine fairly uniquely all the couplings of the gravitino to the other states (such that flat space-time GMSB models are retrieved in the limit of infinite Planck mass).<sup>27</sup> Coupling to supergravity has some other benefits: –the massless spin- $\frac{1}{2}$  goldstino, originating from the spontaneous SUSY breaking in the SBGS, appears as a mixture of the fermions of all chiral (resp. vector) supermultiplets whose F-terms (resp. D-terms) develop vevs, and ceases to be a physical state since it mixes automatically with the massless spin- $\frac{3}{2}$  gravitino giving a mass to the latter. This is the origin of the relation between  $\psi_S$  and  $\tilde{G}$  noted in the previous section, where  $\langle F_{TOT} \rangle$  includes all F-term and D-term vevs –the requirement of an (almost) vanishing cosmological constant, together with that of SUSY breaking, leads to the general relation  $\langle F_{TOT} \rangle \simeq \sqrt{3} m_{\tilde{G}} m_{\text{Pl}}$ , where  $m_{\text{Pl}}$  denotes the reduced Planck mass ( $\simeq 2.4 \times 10^{18} \text{GeV}$ ). Combined with the qualitative relation  $G_F^{-1/2} \sim \frac{\langle F_S \rangle}{M_X}$  between the electroweak scale and the two mass scales at one's disposal in the visible sector, one finds  $m_{\tilde{G}} \sim G_F^{-1/2} \frac{M_X}{\sqrt{3} m_{\text{Pl}} k}$  (where  $k \equiv \langle F_S \rangle / \langle F_{TOT} \rangle$ ), that is typically a very light gravitino in gauge mediated models since  $M_X \ll m_{\text{Pl}}$  (as compared to gravity mediation where it becomes of order the electroweak scale with  $M_X \sim O(m_{\text{Pl}})$ ) –since GMSB generates soft gaugino masses  $M_i$ , the spontaneous SUSY breaking is accompanied by a spontaneous breaking of a continuous R symmetry. The latter leads to an R-axion which is phenomenologically problematic. However, the requirement mentioned previously for the cosmological constant is actually achieved through an additive constant  $W_0 = m_{\tilde{G}} m_{\text{Pl}}^2$  to the superpotential  $W$  of Sec. 3 (if there are no Planck scale vevs), thus breaking explicitly the R symmetry and giving possibly very large masses to the R-axion<sup>28</sup> –including gravity suggests that some discrete symmetries valid in flat space could be violated by non-perturbative quantum gravitational effects, involving for instance black hole physics.<sup>29</sup> In particular, the accidental messenger number conservation responsible for the stability of the LMP can be lost, leading to Planck suppressed decays into MSSM particles through effective (non-)renormalizable messenger number violating (but gauge invariant<sup>30</sup>) operators. Such operators can appear either in the superpotential or in the Kähler potential, the latter being further organized into holomorphic or non-holomorphic in the fields; e.g., taking the SU(5) GUT particle content and messengers in  $\mathbf{5}_M + \bar{\mathbf{5}}_M$ ,

one can have  $K_{\text{hol}} \supset \mathbf{5}_M \bar{\mathbf{5}}_F, \frac{1}{m_{\text{Pl}}} \times \{\bar{\mathbf{5}}_M \bar{\mathbf{5}}_{F,H} \mathbf{10}_F, \mathbf{5}_M \mathbf{10}_F \mathbf{10}_F \dots\}$  and  $K_{\text{non-hol}} \supset \bar{\mathbf{5}}_M^\dagger \bar{\mathbf{5}}_F, \frac{1}{m_{\text{Pl}}} \times \{\mathbf{5}_M^\dagger \bar{\mathbf{5}}_{H,F} \mathbf{10}_F, \bar{\mathbf{5}}_M \mathbf{5}_H^\dagger \mathbf{10}_F, \bar{\mathbf{5}}_M^\dagger \mathbf{10}_F \mathbf{10}_F \dots\}$ ,<sup>31</sup> or in the  $\mathbf{16}_M + \bar{\mathbf{16}}_M$  of SO(10) GUT, one can have operators such as  $K_{\text{hol}} \supset \bar{\mathbf{16}}_M \mathbf{16}_F, \frac{1}{m_{\text{Pl}}} \times \{\mathbf{16}_M \mathbf{16}_F \mathbf{10}_H, \bar{\mathbf{16}}_M \mathbf{16}_F \mathbf{45}_H \dots\}$  or  $K_{\text{non-hol}} \supset \frac{1}{m_{\text{Pl}}} \times \{\mathbf{16}_M^\dagger \mathbf{16}_F^\dagger \mathbf{10}_H, \bar{\mathbf{16}}_M^\dagger \mathbf{16}_F \mathbf{10}_H, \dots \mathbf{16}_M^\dagger \mathbf{16}_F \mathbf{45}_H \dots\}$ .<sup>32</sup> We note here that the supergravity features discussed above lead to an important difference between  $K_{\text{hol}}$  and  $K_{\text{non-hol}}$  after SUSY breaking: the  $K_{\text{hol}}$  contributions go effectively in the superpotential with an extra  $m_{\tilde{G}}$  suppression, i.e.  $W \supset m_{\tilde{G}} \times K_{\text{hol}}$ . As we will see in the following section, the above operators will play an important role in the cosmological fate of the LMP.

## 5. The cosmological set-up

As noted at the end of Sec. 3 the LMP is stable within the minimal GMSB scenarios. If such a particle is produced at the end of inflation, i.e.  $T_{\text{RH}} \gtrsim M_{s-}$ , with  $T_{\text{RH}}$  the reheat temperature, then it will typically overclose the Universe with a relic density  $\Omega_M h^2 \simeq 10^5 \left( \frac{M_{s-}}{10^3 \text{ TeV}} \right)^2$ ,<sup>25,33</sup> unless its mass is finely adjusted. Of course, one can avoid this ‘cosmological messenger problem’ either assuming the LMP to be much lighter than  $\sim 10^3 \text{ TeV}$  or that it is simply too heavy to be produced in the early Universe. However, given our present ignorance of the actual value of  $T_{\text{RH}}$  that can range from 1 MeV up to the GUT scale, and a rough idea about the messenger mass scale  $\gtrsim 10^5 \text{ GeV}$ <sup>d</sup> the LMP is expected to be generically present in the very early Universe. As we will argue, its presence can even play an important role in making the gravitino a viable DM candidate,<sup>33,34,31,35</sup>

In the mass range we consider,  $\mathcal{O}(1 \text{ keV}) \leq m_{\tilde{G}} \leq \mathcal{O}(1 \text{ GeV})$ , the gravitino is easily produced through scattering in the thermal bath (see<sup>36–38</sup> and references therein). Due to its gravitationally suppressed coupling, and in particular that of its spin- $\frac{1}{2}$  component which scales as  $(m_{\tilde{G}} m_{\text{Pl}})^{-1}$ , the leading contribution to the thermal component of its relic density reads  $\Omega_{\tilde{G}}^{\text{th}} h^2 \simeq 0.32 \left( \frac{T_{\text{RH}}}{10^8 \text{ GeV}} \right) \left( \frac{10 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{1/2}}{1 \text{ TeV}} \right)^2$ . (Here  $m_{1/2}$  denotes generically a common value of the gaugino soft masses  $M_i$ .) This illustrates one of the various facets of the so-called *gravitino problem*. The dependence on  $T_{\text{RH}}$ , a

<sup>d</sup>indeed, requiring the MSSM soft masses to be  $\lesssim 1 \text{ TeV}$  implies  $\frac{\langle F_S \rangle}{M_X} \lesssim 10^5 \text{ GeV}$ . Furthermore,  $M_{s-}^2 \geq 0$  imposes  $\langle F_S \rangle \leq M_X^2$ , thus leading to  $M_X \gtrsim 10^5 \text{ GeV}$  which gives the mass scale of the LMP, barring fine-tuned values.

parameter so far still poorly connected with the particle physics modelling, is theoretically annoying as it requires a high level of adjustment, with basically no other observational consequences than providing an observationally consistent abundance for the gravitino if it is to play the role of DM. Perhaps more importantly, depending on the values of  $m_{\tilde{G}}$  and  $m_{1/2}$  (and other parameters of the MSSM), the gravitationally suppressed decay into (or of) the gravitino, depending on whether it is the LSP or the next to LSP (NLSP), can equally strongly affect the success of the standard Big Bang nucleosynthesis (BBN) predictions; we comment further these issues at the end of the section. On top of  $\Omega_{\tilde{G}}^{\text{Th}}$  the gravitino abundance can have substantial non-thermal contributions from the decay of whatever heavier relic particles, if such decays occur after these particles have dropped out of thermal equilibrium. For instance, if only MSSM particles are present, one gets a non-thermal contribution  $\Omega_{\tilde{G}}^{\text{non-th}} h^2 = \Omega_{\text{NLSP}} h^2 \frac{m_{\tilde{G}}}{m_{\text{NLSP}}}$ , where  $\Omega_{\text{NLSP}} h^2$  is the abundance of the essentially thermally produced NLSP which can be a neutralino or a stau, akin to point *i*) of Sec. 1.  $\Omega_{\tilde{G}}^{\text{non-th}} h^2$  is often taken as the main source of gravitino abundance in scenarios of gravitino DM with  $m_{\tilde{G}} \gtrsim 150 \text{ GeV}$  (motivated by gravity mediation),<sup>8</sup> forgetting altogether the uncertainties from  $\Omega_{\tilde{G}}^{\text{th}} h^2$ . We stress here that in GMSB scenarios one cannot play successfully a similar game since, due to the lightness of the gravitino, the above  $\Omega_{\tilde{G}}^{\text{non-th}} h^2$  cannot account alone for the observations as illustrated in Fig. 2 where the scan extends up to  $m_{\tilde{G}} = 100 \text{ GeV}$  and the NLSP is a stau. It is then interesting to note that for a gravitino  $\gtrsim 1 \text{ GeV}$  (and  $m_{\text{stau}} \approx 200 \text{ GeV}$ , a typical configuration for a not too fine-tuned GMSB) one needs a thermal component with  $T_{\text{RH}} \gtrsim 5 \times 10^6 \text{ GeV}$  in order to reach a suitable gravitino DM abundance. Such values of  $T_{\text{RH}}$  become of order the LMP mass suggesting that the LMP (and perhaps other heavier states of the messenger/spurion sectors) will be present in the early Universe. If so, a different thermal history may occur, modifying the usual MSSM based estimates. This brings us to the crux of the scenario:  $T_{\text{RH}}$  can be anywhere all the way up to very large values. Part or all of the GMSB sectors (Fig. 1) are thus present early on in the thermal bath and contribute to the thermal production of the gravitino which is then typically very large. As stressed at the beginning of this section the LMP decouples from the thermal bath with a very large abundance causing potentially an overclosure problem. However the LMP is likely to decay through Planck suppressed or gravitino suppressed operators as discussed at the end of Sec. 4. Such late decays occur typically after the LMP freeze-out and would substantially dilute the gravitino abundance through entropy

release if they occur at a temperature where the LMP dominates the Universe *and* after the gravitino has decoupled from the thermal bath. Thus, the scenario entails the calculation of the LMP thermal relic density yield  $Y_M$  and messenger decay width  $\Gamma_M$ , and a comparison among its freeze-out temperature  $T_M^f$ , decay temperature  $T_{\text{dec}} \sim \Gamma_M^{1/2}$ , matter domination temperature  $T_{MD} \simeq \frac{4}{3}M_{s-} \times Y_M$  as well as the gravitino freeze-out temperature. One finds a substantial part of the parameter space such that the diluted gravitino abundance is consistent with WMAP and can represent the (cold) dark matter however large  $T_{\text{RH}}$  may be! We show an example in Fig. 3 for  $T_{\text{RH}}$  as large as  $10^{12}$  GeV in the case of  $\mathbf{5}_M + \bar{\mathbf{5}}_M$  of SU(5) and with the first operator of  $K_{\text{hol}} \supset \mathbf{5}_M \bar{\mathbf{5}}_F$  given in Sec. 4 for illustration. One sees that the details of the messenger/spurion sectors can have an important effect on the viability of the DM scenario. For instance the small red-hatched area in the left-hand panel of Fig. 3 corresponds to gravitino DM solutions in the scenario of<sup>33</sup> where  $\langle F_S \rangle \simeq \langle F_{\text{TOT}} \rangle$ . However it corresponds to a spurion much heavier than the LMP in a parameter space region (above the dashed black line) where spurion mediated LMP annihilation into gravitinos violates perturbative unitarity, thus theoretically unreliable. In contrast, viable solutions exist when the spurion is lighter than the LMP, as shown by the green/yellow region on the right-hand panel. A systematic study including other possible operators has been carried out in.<sup>31</sup> A more promising case is the  $\mathbf{16}_M + \bar{\mathbf{16}}_M$  of SO(10). The LMP being an MSSM singlet in this case, its interaction with the thermal bath is loop suppressed leading to a much higher  $Y_M$  than in the SU(5) case for comparable  $M_{s-}$ . Taking into account the decay induced by  $K_{\text{hol}}$  or  $K_{\text{non-hol}}$ , one finds gravitino DM solutions when the spurion is much heavier than the LMP, but this time in regions where perturbative unitarity remains reliable,<sup>35,31,32</sup> By the same token, one can justify here not considering explicitly the SBGS and messenger sectors (left-hand part of Fig. 1) by assuming them to be much heavier than the LMP, thus playing a role similar to that of the spurion (i.e. essentially gravitational contributions to LMP annihilation into gravitinos).<sup>e</sup>

Finally, let us briefly discuss the issue of primordial nucleosynthesis of the light elements which constitutes an important observational probe of the earliest epochs of the thermal history. A late decaying particle from physics beyond the SM (with a lifetime  $\tau \sim \mathcal{O}(1 \text{ sec})$ ) can affect the successful standard big bang nucleosynthesis (SBBN) predictions through ei-

<sup>e</sup>obviously these sectors could offer DM candidates, or lead to cosmological closer problems on their own. In this case they can be treated along similar lines quite symmetrical to the ones considered in the present study.



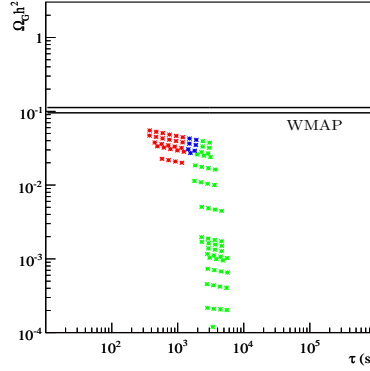


Fig. 2. The non-thermal stau-NLSP decay contribution  $\Omega_{\tilde{G}}^{\text{non-th}} h^2$  to the gravitino abundance versus the NLSP lifetime, with  $N_{\text{mess}} = 2$ ,  $M_{s-} = 5 \times 10^6 \text{ GeV}$ ,  $\tan \beta = 10$ ,  $10 \text{ MeV} \leq m_{\tilde{G}} \leq 100 \text{ GeV}$  and a scan over  $\Lambda$ , taken from<sup>39</sup>. The horizontal band corresponds to the  $0.095 < \Omega_{\text{CDM}} h^2 < 0.136$  WMAP consistent region. (see Fig. 4 for the green/red color code.)

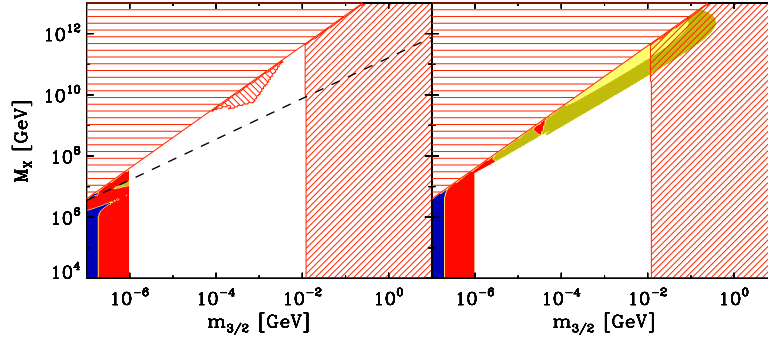


Fig. 3. sneutrino-like LMP versus gravitino masses. The spurion is heavier (lighter) than the LMP in the left-hand (right-hand) panel. Green/yellow region corresponds to gravitino cold DM with  $\Omega_{\tilde{G}} h^2 < 0.3$ ;  $T_{\text{RH}} = 10^{12} \text{ GeV}$ . (red/blue correspond to warm/hot gravitinos); the NLSP is assumed to be a 150 GeV Neutralino, decaying mainly into a photon (or a Z-boson) and a gravitino. The red-hatched bands to the right of each panel indicate the  $m_{\tilde{G}}$  regions where this decay occurs after  $\sim 1$  sec, thus potentially affecting primordial nucleosynthesis. Taken from<sup>31</sup> to which we refer for further details.

ther electromagnetic injections or hadronically induced nuclear reactions<sup>f</sup>. This possibility has become particularly interesting in the perspective of solving a problematic deviation from SBBN of the  $^7\text{Li}$  and  $^6\text{Li}$  inferred observational abundances in low metallicity stars. Moreover, a very efficient catalyses of the  $^6\text{Li}$ -producing reaction can occur if the decaying particle is

<sup>f</sup>see for instance,<sup>40, 41, 42</sup> and references therein and thereout.

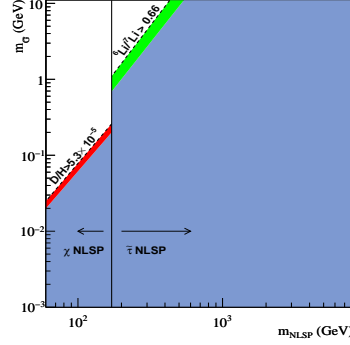


Fig. 4. Gravitino versus NLSP masses. same GMSB parameters as in Fig. 2;  ${}^7\text{Li}/\text{H} < 2.5 \times 10^{-10}$  (red);  $0.015 < {}^6\text{Li}/{}^7\text{Li} < 0.66$  (green); SBBN:  $Y_p \leq 0.258$ ,  $1.2 \times 10^{-5} \leq \text{D}/\text{H} \leq 5.3 \times 10^{-5}$ ,  ${}^3\text{He}/\text{D} \leq 1.72$  (light blue); taken from.<sup>44</sup>

electrically charged and sufficiently long lived.<sup>43</sup> Constraints on physics beyond the SM are thus of two types: conservative (consistency with SBBN) or speculative (solving the Lithium problems). We illustrate these two features in Fig. 4 within the GMSB context,<sup>44</sup> showing the effect of the nature of the NLSP on the lithium yields.

In this respect, it is to be noted that the LMP decays typically at temperatures  $\mathcal{O}(100\text{MeV})$  if  $M_{s-} \geq 10^3\text{TeV}$ , thus rendering the gravitino DM scenarios we have described here quite safe from the BBN perspective. Nonetheless, one should keep in mind that it remains exclusively a task for the colliders to ultimately favor or disprove GMSB scenarios.

## Acknowledgments

My thanks go to the organizers of DARK 2009 for the very enjoyable atmosphere and the quite diversified topics of the conference. This work was supported in part by ANR under contract NT05-1\_43598/ANR-05-BLAN-0193-03.

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